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H1P PMA

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GB 0840950 A EP 0033803 A2 US 4663551 A

(58) Field of Search
UK CL (Edition R) H1P PMA , H2A ARC2 ARC4A
INT CL^7 H02K 41/03 41/035

(54) Abstract Title

Tapered pole pieces for a linear electromagnetic machine

(57) A linear electromagnetic machine consisting of an armature and stator one of which includes a plurality of axially magnetised annular magnets 106 and pole pieces 107 arranged to produce a radial magnetic field and the other of which includes a plurality of circumferential conductive elements wherein the pole pieces of the magnets taper radially away from the conductive elements. Non magnetic filler 109 may be used. A control system is described.

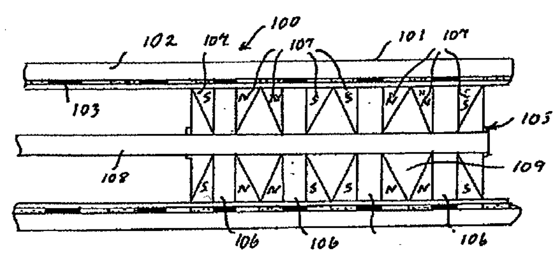

Fig 1

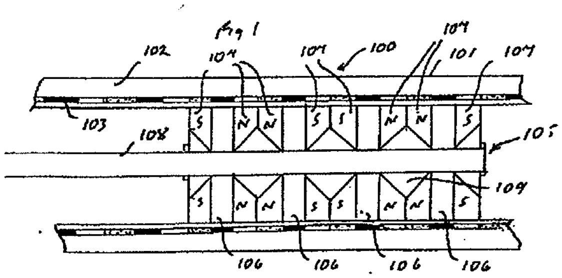

Fig 2

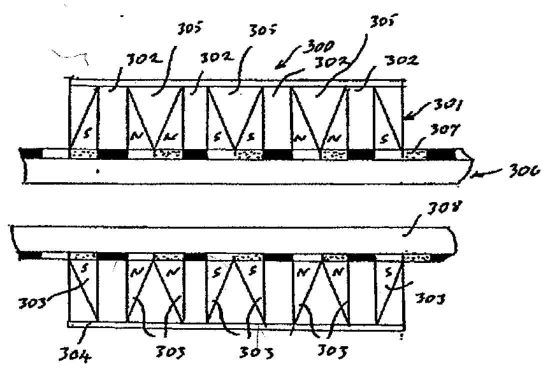

Fig 3

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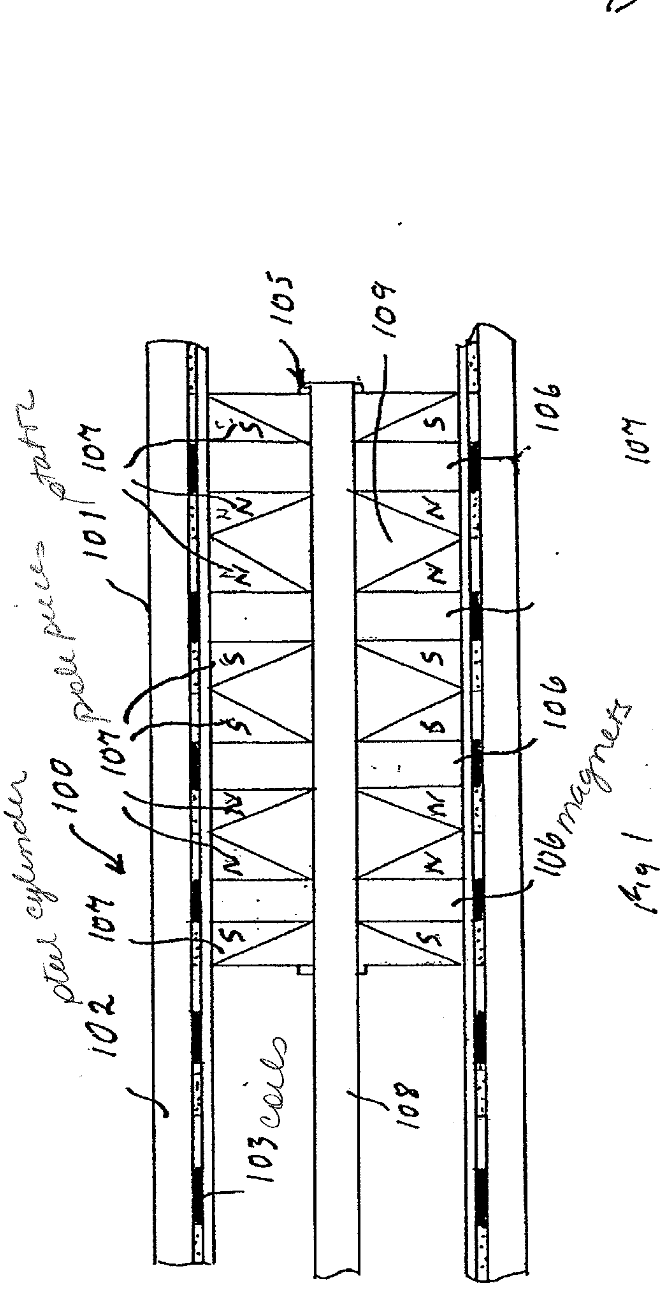
steel cylinder
102
103 coils
108
100
104
pole pieces
101
stator
105
109
106
106 magnets

Fig 1

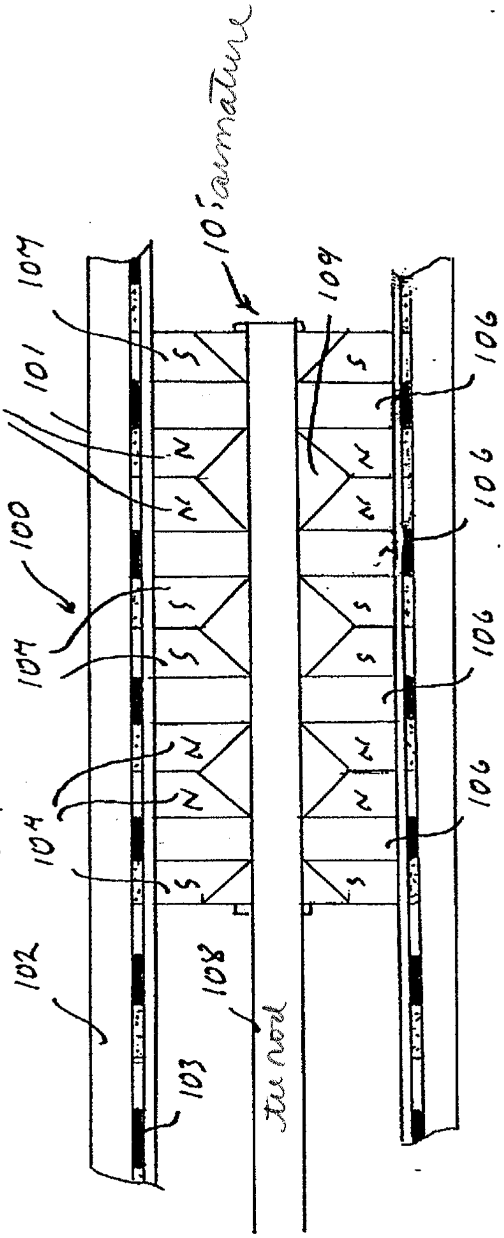
105 armature
109
104
101
100
106
102
103
108
tie rod

Fig 2

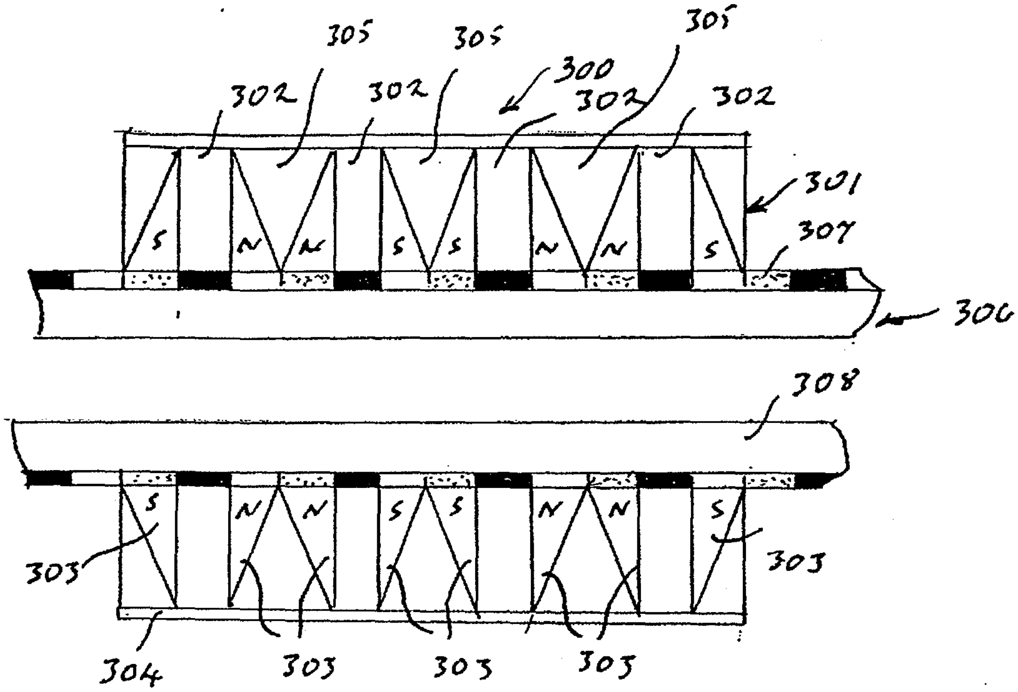
305
305
305
300
302
302
302
302
301
307
S
N
N
S
S
N
N
S
306
308
303
303
304
303
303
303

Fig 3

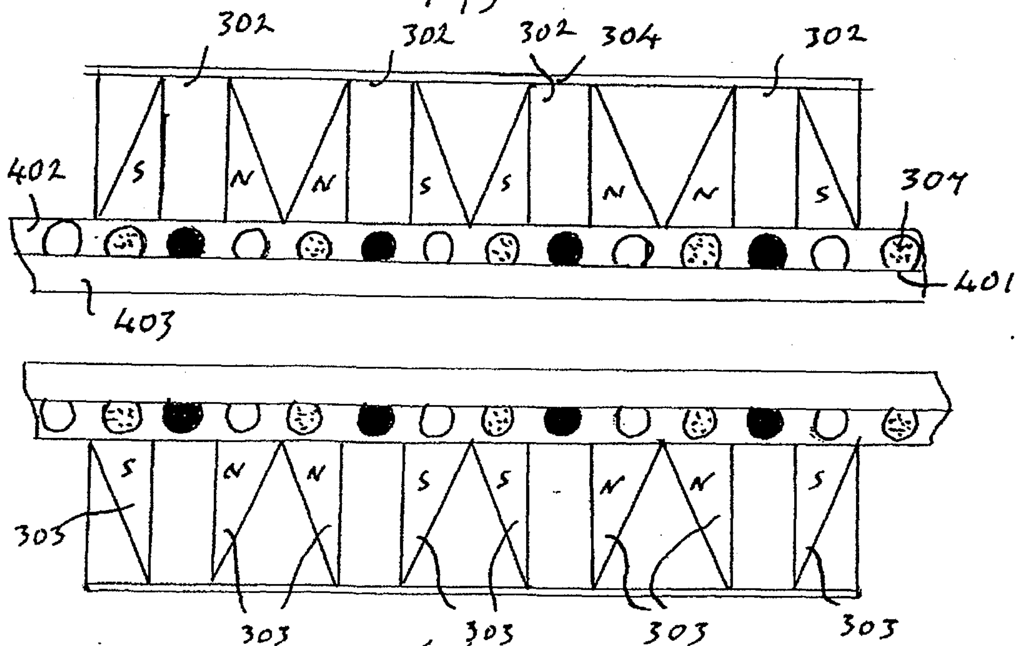
302
302
302
304
302
402
307
401
403
S
N
N
S
S
N
N
S
303
303
303
303
303

Fig 4

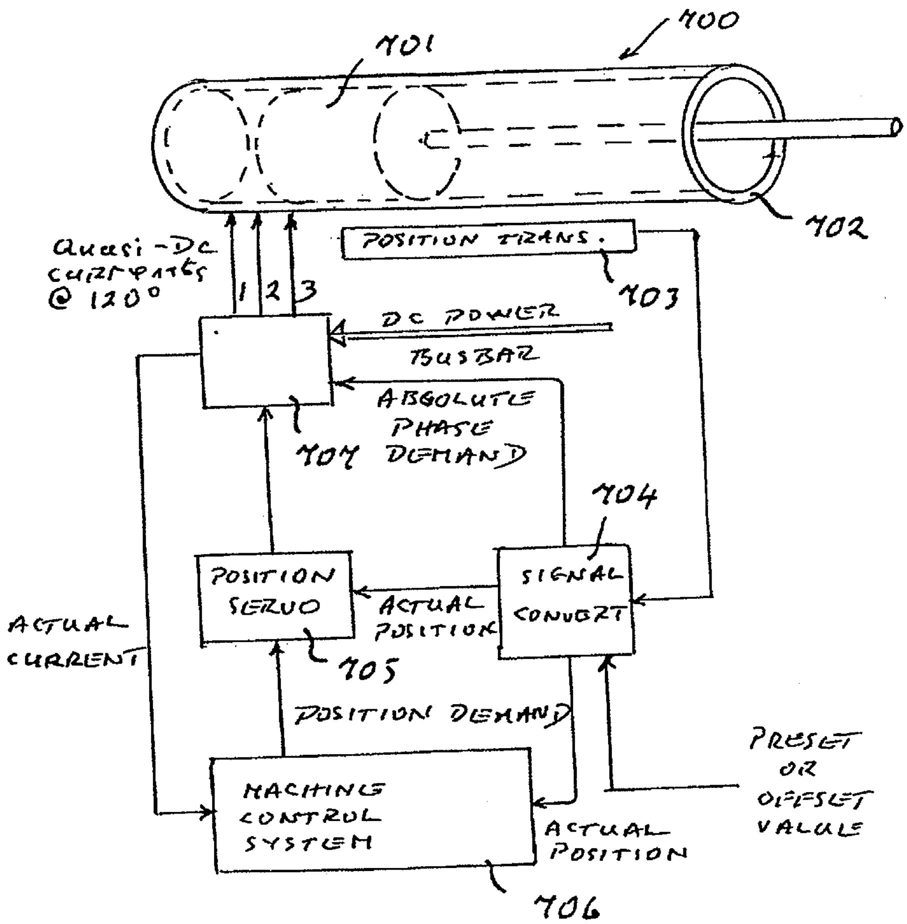
700
701
702
Quasi-DC currents @ 120°
1
2
3
POSITION TRANS.
703
DC POWER
BUSBAR
ABSOLUTE PHASE DEMAND
707
704
POSITION SERVO
ACTUAL POSITION
SIGNAL CONVERT
ACTUAL CURRENT
705
POSITION DEMAND
PRESET OR OFFSET VALUE
MACHINE CONTROL SYSTEM
ACTUAL POSITION
706

Fig 5

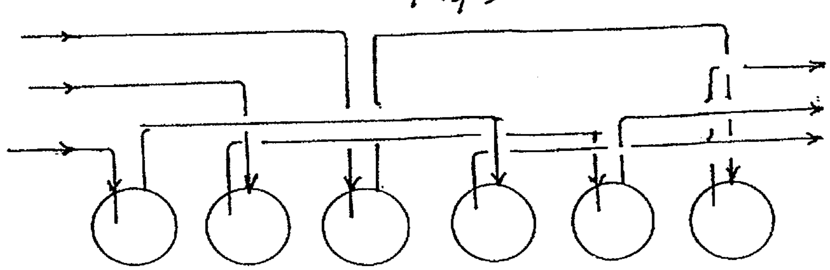

Fig 6

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A LINEAR ELECTROMAGNETIC MACHINE

The present invention relates to a linear electromagnetic machine, particularly one which is cylindrical in form, and more specifically, to such a machine in which an armature is urged to move within a surrounding stator by electromagnetic forces produced by interactions between radial magnetic fields and electric currents flowing in circumferential coils, the radial magnetic fields being produced by annular axially magnetised permanent magnets forming part of the armature and the coils forming part of the stator, or vice versa.

Such machines may be used to produce linear motion, or to maintain the position of a body against forces exerted upon it. If the ends of the cylindrical stator are closed and suitable valves are provided then such machines also may be used as pumps. An annular geometry for the permanent magnets can be adopted for a number of reasons. For example to lighten an armature; to provide an axial passage through which a tie-rod can be passed to clamp the components of an armature together; or to provide a central space in which components can be placed or through which fluids can be caused to pass. Co-pending application describes forms of electromagnetic machine in which the armature or the stator includes magnets having this annular geometry.

The thrust generated by a linear electromagnetic machine may be described by the equation T = B*I*L where T is the thrust in Newtons, B is the flux density in Tesla, I is the current in a wire or coil in amps and L is the length of the wire in the coil in metres. It follows directly from this relationship that the volume of copper in the wire that must be intersected by the magnetic flux is given by V = P/(B*d) where V is the volume in cubic metres and d is the current density in the wire in amps per square metre.

It follows also that the electrical power required to produce this thrust when the machine is stationary is given by the relationship W = P*r*d/B where W is the power in watts and r is the resistivity in ohm metres.

It will be appreciated, therefore, that the performance of a linear electromagnetic machine can be improved by ensuring that the magnetic flux is concentrated as much as possible in the regions where it intersects the coils. In the case where the armature includes axially magnetised permanent magnets and pole pieces having an annular geometry, there will be a tendency for there to be a leakage flow of magnetic flux inwards through the central hole in the armature instead of outwards through the coil of the stator. This leakage represents a decrease in the thrust generated per ampere of energising current, and of course, it is desirable that this should

be minimised.

Another type of linear electromagnetic machine is the inverse of that described above, in that the magnets and pole pieces are part of the stator assembly and the energising coils are wound on the periphery of the armature. In this case, there will be a tendency for an outward leakage of flux. Again, this is undesirable, both because of the reduction of the flux density in the region of the armature coils, and because of the electromagnetic interference that such stray magnetic fields can cause.

In both cases, therefore, it is desirable that magnetic flux leakage should be reduced.

According to the present invention there is provided a linear electromagnetic machine having a generally cylindrical geometry including a first member comprising at least one axially magnetised annular magnet and associated annular pole pieces, the magnet and pole pieces being arranged to produce a magnetic field with a radial component, a second member including a plurality of circumferential conductive elements so positioned as to be intersected by the radial component of the magnetic field produced by the magnet and pole pieces, whereby electric currents flowing in the conductive elements interact with the magnetic field to provide an axial

force tending to cause a relative motion between the first and second members, wherein the cross-sectional area of the pole pieces reduces radially away from the said conductive elements.

In a first embodiment of the invention the first member forms part of the armature of the machine and the second member forms part of a cylindrical stator in which the armature moves, or is urged to move.

In neither case is it necessary for the pole pieces to reduce in cross section over their entire radial dimension. A reduction over a part only, for example half the radial extent may be adequate.

A central hole or passage through the machine is preferably provided to house one or a number of transducers for control purposes, in particular a position transducer may be housed in such a passage. The passage may be defined by a high permeability sleeve whereby effectively to shield the transducer or transducers from the influence of the strong magnetic fields in the machine.

The invention will now be described, by way of example, with reference to the following drawings, in which,

Figure 1 is a schematic longitudinal section of the first embodiment of the invention;

Figure 2 is a schematic longitudinal section of a second form of the first embodiment of the invention;

Figure 3 is a schematic longitudinal section of a second embodiment of the invention;

Figure 4 is a schematic longitudinal section of a second form of the second embodiment of the invention;

Figure 5 illustrates how electrical coils associated with both embodiments of the invention are energised; and

Figure 6 shows, schematically, a control system for use with any of the above.

Referring first to Figure 1, an electromagnetic ram 100 has a stator assembly 101 with a steel outer cylinder 102 which surrounds a series of circumferential coils 103. The coils 103 have a rectangular cross section and are wound upon a lining tube 104 which provides a bearing surface for an armature 105. The armature 105 primarily comprises a series of axially magnetised permanent magnets 106 and annular pole pieces 107 which taper radially outwards. The magnets 106 are arranged with like poles adjacent and the pole pieces 107 serve to direct the magnet fluxes of the magnets 106 radially outwards to intersect the coils 103 before travelling through the outer steel cylinder 102, passing inwardly through the coils 103 and re-entering the magnets 106. In this embodiments the magnets 106, pole pieces 107 and coils 103 of the stator 101 all have the same axial length but this need not necessarily be the case in all

embodiments.

The pole pieces 107 taper outwardly at such an angle that they are close to magnetic saturation throughout. Any inward flow of the magnetic flux will require the local flux density to increase. If the material of the pole pieces 107 however is close to saturation already, then the inward magnetic flux is "choked off" by the saturation of the pole pieces 107, so directing the magnetic flux outwards and maximising its interaction with the coils 103 of the stator assembly 101, and hence the efficiency of the linear electromagnetic machine 100. Any slight leakage of flux inwardly can be absorbed by providing a mild steel tube as a lining for the central hole through the armature assembly 106. Such an arrangement also improves the mechanical stability of the armature assembly.

The magnets 106 and the pole pieces 107 are clamped together tightly by a tie-rod or tube 108 which also acts as a piston rod. The tie-rod 108 is made of a non-magnetic steel so as to avoid a central magnetic short circuit between the faces of the magnets 106. In order to facilitate the clamping together of the components of the armature assembly 106, the spaces 109 resulting from the radial tapering of the pole pieces 107 are filled with a nonmagnetic metal, such as aluminum, or a resin based material.

In practice it is not necessary for the pole pieces 107 to taper over the whole radial distance; it has been found that about half the radial distance is adequate, and such an arrangement is shown in Figure 2. This arrangement is stronger mechanically than that shown in Figure 1, which is an advantage because the mechanical stresses within the armature assembly 106 in use can be very high, but on the other hand, it is heavier than the arrangement shown in Figure 1, which can be a disadvantage.

An alternative configuration of linear electromagnetic machine is the inverse of that described previously in that the magnet and pole pieces are part of the stator assembly and the coils are wound on the periphery of the armature. As pointed out previously, in this case, there will be a tendency for the outward leakage of magnetic flux, which not only reduces the efficiency of such electromagnetic machines but can cause damage to nearby electrical equipment and destroy magnetically stored data.

As before, this problem can be alleviated by tapering the pole pieces, in this case, outwardly. Figure 3 is a diagramatic representation of an embodiment of the invention having this configuration.

Referring now to Figure 3, linear electromagnetic machine 300 includes a stator 301 having a plurality of annular axially magnetised magnets 302 and associated pole pieces 303 contained within a steel shell 304. As before, the pole pieces taper, but in this case in the opposite sense. Again the spaces 305 between the pole pieces 303 are filled with a non-magnetic metal or a resin based material. The assembly is clamped together with tie-rods which are not shown in the drawing. An armature 306 consists of a series of coils 307 wound upon a high permeability tubular core 308 and kept in position by end flanges, which are not shown in the drawing. In order to provide the high hoop resistance which is necessary in this embodiment of the invention the core 308 is either constructed of insulated longitudinally orientated rods or wires, or has a slot cut into or otherwise formed in it.

As in the first embodiment of the invention, the coils 307 have a rectangular cross section and the magnets 302, pole pieces 303 and coils 307 all have the same axial length.

If desired the inertia of the armature can be reduced by attaching the high permeability sleeve to the stator structure and winding the coils 307 on a lining which slides upon the high permeability core 308. It is to be noted that the hollow core 308 ensures that there is only

a very small magnetic field at the centre of the armature 306, making this form of linear electromagnetic machine suitable for use with internal instrumentation.

Figure 4 shows a similar section of a second embodiment of the invention in which the armature coils 307 are wound into circumferential slots 401 cut into a sleeve 402 which surrounds a central armature flux return tube 403. The remainder of the components are the same as those in the embodiment of Figure 3 and have the same reference numerals.

In both cases the pole pieces do not have to taper over their entire radial dimension, as before. Figure 5 shows how the coils of each embodiment of the invention are interconnected. The coils are connected in three phases alternately, each coil being in opposite connection to the adjacent two coils, so that there are six coils in each complete group. The axial length of the six coils is also the distance between like magnetic poles of the magnet assembly and this distance is referred to as the magnetic period of the linear electromagnetic machine.

Figure 7 shows diagrammatically a control system suitable for controlling a linear electromagnetic machine such as described above so as to cause the machine to respond to a position demand for an item connected to the armature of the machine.

Referring to Figure 7 an electromagnetic machine 700 includes an armature 701 which moves in a stator 702. As shown, the stator 702 is equipped with a coil system such as those described above. A linear position transducer 703, of any convenient type, is arranged to produce position signals indicative of the actual position of the armature 701. The position signals may be analogue or digital in nature and are applied to a signal converter 704. The signal converter 704 may be a software module, although as a fast update rate is necessary, it may be better to perform the conversion operation in dedicated hardware.

If the output signal from the signal converter 704 is of analogue form, it is first converted to a numerical value with the appropriate scale and offset parameters so that it represents the true position of the armature 701 in relation to the apparatus which the machine 700 forms a part. If the position transducer 703 produces an incremental (two phase digital signal), this is processed by a counter, not shown in the Figure but which is reset to zero at the tare or calibration position of the machine 700.

The armature 701 position value is then passed to a servo controller 705, where it is compared with the desired position of the part of the apparatus to which the

machine 700 is connected, so as to produce a current amplitude demand signal. The current amplitude demand signal is passed to a three-phase power driver module 706 which acts to produce three quasi DC currents at phase angles separated by 120° which are applied to the groups of coils in the stator 702. The armature 701 position value also is buffered and is passed to an overall machine control and monitoring system 707. Signals relating to the DC currents applied to the coils of the stator 702 also are supplied to the machine control system 707.

The armature position value is compared in the machine control and monitoring system with an offset value which defines the starting point of the cyclic phase control system from the stator coils. This offset value may be preset manually or it may be determined automatically as part of a starting BITE operation which measures the acceleration of the armature at the constant current, as a function of a varying offset in a "hill-climbing" sequence. As the linear period of the cycle of the coil currents is a fixed value which is defined by the dimensions of the armature 701 of the machine 700, the optimum phase angle for the quasi DC currents for any position of the machine 700 can then be passed to the power drive module 706.

CLAIMS

1. A linear electromagnetic machine having a generally cylindrical geometry including a first member comprising at least one axially magnetised annular magnet and associated annular pole pieces, the magnet and pole pieces being arranged to produce a magnetic field with a radial component, a second member including a plurality of circumferential conductive elements so positioned as to be intersected by the radial component of the magnetic field produced by the magnet and pole pieces, whereby electric currents flowing in the conductive elements interact with the magnetic field to provide an axial force tending to cause a relative motion between the first and second members, wherein the cross-sectional area of the pole pieces reduces radially away from the said conductive elements.

2. An electromagnetic machine according to Claim 1 wherein the pole pieces taper over the whole radial dimension thereof to obtain the said reduction in cross-sectional area.

3. A linear electromagnetic machine according to Claim 1 wherein the pole pieces taper over only part of the radial dimension thereof to obtain the said reduction in cross-sectional area.

4. A linear electromagnetic machine according to Claim 3 wherein the pole pieces taper over approximately half their radial dimension.

5. A linear electromagnetic machine according to any preceding Claim wherein the conductive elements form part of the stator and the magnets form part of the armature of the machine the said armature being adapted to move within the stator.

6. An electromagnetic machine according to Claim 5 wherein there is provided a high permeability metal sleeve lining a central hole through the armature assembly.

7. A linear electromagnetic machine according to any of Claims 1 to 4 wherein the magnets and associated pole pieces form part of the stator and the conductive elements form part of the armature.

8. A linear electromagnetic machine according to Claim 7 wherein the armature assembly includes a hollow high permeability core.

9. A linear electromagnetic machine according to Claim 7 or Claim 8 wherein the stator assembly includes a high permeability sleeve enclosing a magnet or magnets and pole pieces.

10. A linear electromagnetic machine according to any preceding Claim wherein the total number of conductive elements is divisible by three and the conductive elements are connected in three phases alternately each conductive element being in opposite connection to adjacent conductive elements, six conductive elements forming a magnetic period of the machine.

11. A linear magnetic machine according to any preceding Claim wherein there is included a plurality of magnets and associated pole pieces positioned with like poles adjacent so as to provide an axially alternating radial magnetic field.

12. A linear electromagnetic machine according to Claim 11 wherein the axial separation between like magnetic poles is equal to the magnetic period of the machine.

13. A linear electromagnetic machine according to any preceding Claim wherein the conductive elements are coils wound upon a ferromagnetic core.

14. A linear electromagnetic machine according to Claim 12 wherein the coils are wound in slots in a ferromagnetic former.

15. A linear electromagnetic machine according to Claim

13 wherein the former includes at least one axial discontinuity to increase the hoop resistance thereof.

16. A linear electromagnetic machine according to Claim 13 or Claim 14 wherein the coils have a rectangular cross-section.

17. A linear electromagnetic machine according to Claim 13 or Claim 14 wherein the coils have a symmetrical cycloid cross-section.

18. A linear electromagnetic machine substantially as herein before described with reference to Figures 1 and 2 or 3 and 4 and 5 the accompanying drawings.

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INVESTOR IN PEOPLE

Application No: GB 0001620.4
Claims searched: 1-18

Examiner: John Cockitt
Date of search: 15 August 2000

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.R): H2A [ARC4A, ARC2]; H1P [PMA]

Int Cl (Ed.7): H02K [41/03, 41/035]

Other:

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X	GB0840950A	BENDIX - see fig 3	1 at least
X	EP0033803A2	NATIONAL - see pole pieces 46-52	1 at least
X	US4663551A	WEH - see figs	1 at least

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
		E	Patent document published on or after, but with priority date earlier than, the filing date of this application.
&	Member of the same patent family		